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Out-of-focus intensity distribution:
effects of focal number and aberration

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Abstract

Shock wave experiments contemplated on powerful CO₂ lasers require uniform planar illuminations over spot sizes much larger than the diffraction limit focal spot size of the focusing optics. Cost as well as space considerations limit one's choice of optics to parabolic mirrors with focal lengths between 78 and 150 cm, and apertures to 35 cm. Within these constraints one either modifies the incident laser energy distribution to modify the focal spot shape, or works out of the focal plane. I analyze the latter option using a fast Fourier method to calculate the intensity distributions for two focal lengths (78 and 132 cm) and various measured optical distortions (Phase only) for the focusing optics. I found that a 78 cm element produced more uniform spots of diameter 500 μ m. The 132 cm element was less sensitive to focusing/positioning error than the 78 cm element.

Introduction

In many of the experiments that study the interaction of laser radiation with matter, one would like to have as uniform an irradiance as possible in order to define one quantity rather than a range for the intensities. Another requirement, characteristic of shock wave experiments, is the desirability to generate plane shock waves. This is usually accomplished by having the area of the shock wave much larger than the target thickness in the direction of the travel of the shock. For CO₂ lasers the areas contemplated are between 400 and 600 μ m. The uniformity of the laser spot is not very critical since the shock wave pressure (and its speed) profile is weakly dependent on the laser intensity, $P \sim I^{2/3}$.¹ Whilst pressure is not measured directly, the shock speed, a measurable quantity, in the limit of high pressures is proportional to the square root of the pressure. Thus $v \sim I^{1/3}$, and hence

$$\Delta v/v = \Delta I/3I. \quad (1)$$

To get 10% variation in the shock velocity one can tolerate 30% non-uniformity in the laser drive.

Using powerful CO₂ lasers such as the Gemini or Helios Systems at LANL, very few alternatives exist for the production of uniform illumination over small spot areas. The most common method is to defocus the optics then use a small part of the illuminating beam. In the design of the MARS laser we had the option of choosing the focal length of the focusing parabolas in order to: minimize the wasted beams; minimize the sensitivity to positioning (focusing); and maximize the uniformity of the spot illumination. Physical constraints limited the choice to 35 cm diameter focusing optics with a focal length of either 78 or 132 cms.

The present study utilized the Laser Optical Train Simulator (LOTS) code developed by G. Lawrence.² In the study I have also included the effects of optical aberrations on the intensity distributions. The aberrations I included were actually measured aberrations of typical optical elements that were utilized in LANL laser systems.

Computations

The central part of the computation is the evaluation of the Fresnel-Kirchoff diffraction integral for the wave amplitude³:

$$U(u, v, \psi) = - \frac{1}{\lambda} \frac{A_0^2}{R^2} e^{-iu(R/a)^2} \int_0^1 \int_0^{2\pi} e^{-in(k, \rho, \theta, \psi)} \rho d\rho d\theta \quad (2)$$

k is the wave number, λ is the wave length and n is the phase;

$$n(k, \rho, \theta, \psi) = k\Phi(\rho, \theta) - v\rho \cos(\theta - \psi) - \frac{1}{2} u \rho^2 \quad (3)$$

where: R is the radius of the Gaussian reference sphere that passes through the center

of the focusing optics; a is the radius of the focusing optics pupil; and u and v are the two "optical coordinates" with respect to the image point. When there is no aberration:

$$u = r \sin \psi = \frac{2\pi}{\lambda} \left(\frac{a}{R}\right)^2 z \quad (4)$$

$$v = r \cos \psi = \frac{2\pi}{\lambda} \left(\frac{a}{R}\right) (x^2 + y^2)^{1/2} \quad (5)$$

$\Phi(\rho, \theta)$ is the aberration function, and represents the deviation of the wave front from the spherical (Gaussian) wavefront at the exit pupil of the focusing optics. The aberration function is usually deduced from measured interferograms using a fringe reduction program FRINGE.⁴ The aberration function is expanded in a power series of Zernike circular polynomials and is stored. Table I shows the first eight polynomials, in the order stored in the computer, as well as typical numbers that were used in the present study. The optical path difference OPD is calculated as follows:

$$OPD = \lambda \sum_{n=1} C_n R_n(\rho, \theta) \quad (6)$$

TABLE I

Term	Polynomial	Correspondence	SALT/1	PAR/1	PAR/2
1	1	Constant	+0.0000	-0.0003	+0.0000
2	$r \cos \theta$	Tilt	+0.0000	+0.0029	-0.0038
3	$r \sin \theta$		+0.0001	-0.0021	-0.0045
4	$2r^2 - 1$	Defocus	-0.0100	-0.2205	+0.0018
5	$r^2 \cos 2\theta$	Astigmatism &	-0.0410	-0.0135	-0.0898
6	$r^2 \sin 2\theta$	Defocus	+0.0671	-0.0615	+0.0250
7	$(3r^2 - 2) r \cos \theta$	Coma &	-0.0178	-0.1202	+0.0193
8	$(3r^2 - 2) r \sin \theta$	Tilt	-0.0692	+0.5330	-0.0348

The source is usually divided into a 64 x 64 matrix of points. A fast fourier transform method is then used to calculate the intensity and phase distributions in any required plane. Figure 1 shows the OPD map at the exit pupil of the optics.

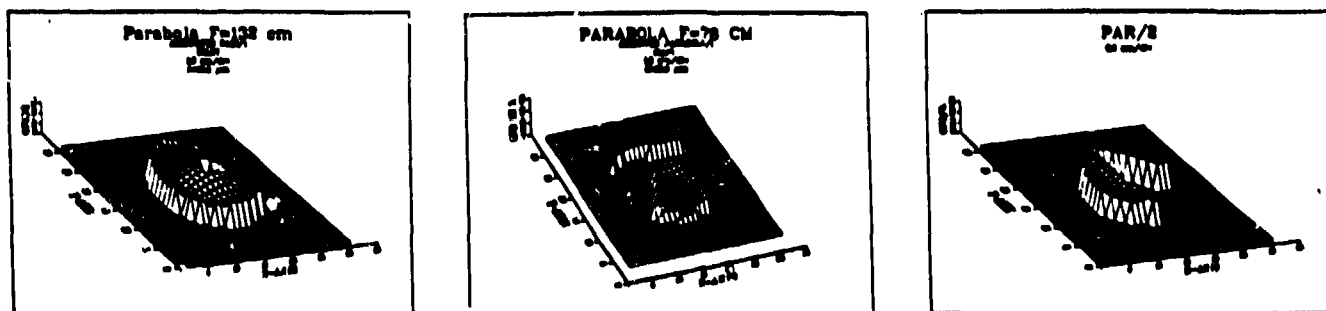


Fig. 1. OPD map of the aberrations corresponding to Table I. a) is for the salt window; b) is for the older parabola/1; and c) is for the new parabola/2.

Effects of aberrations

Many calculations have been made to investigate the effect of individual aberrations on the image intensity distribution.^{5,6} However, in the present case we were interested in the total effect of real measured aberrations on the intensity distributions out of the focal plane. For a given "Geometric" radius, the optical parameters u and v are equal. Hence, the out-of-focus axial position Z , where the spot size equals the geometric radius r_g is given by:

$$Z = (f/a) r_g \quad (7)$$

where f is the focal length of the focusing element. For $a=17.5$ cm, $f = 132$ cm, $r_g = 250$ μ m, and $Z = 2000$ μ m. The effects of the three aberrations listed in Table I are shown in the three dimensional plots of Fig. 2. The intensity is plotted in a plane perpendicular to the optics axis, and at a distance of -2000 μ m from the unaberrated focal position. The negative number means we are shifted towards the focusing optics. The companion Fig. 3 shows a slice along the y axis through the center of the spot.

It is interesting to note that the effect of the parabola/2 aberrations was much less than those from parabola/1. The parabolas were both diamond turned, but represent two vintages. Parabola/2 was vintage 1979 while parabola/1 was vintage 1976. Considerable improvement in machining quality is evident. Parabola/1 had ODP error of $\lambda/10$ RMS [0.6 λ peak to valley], while parabola/2 had an RMS OPD error of $\lambda/25$ [corresponding to a peak to valley error of $\lambda/5$]. The effects of the aberrations of parabola/2 was not only to shift the focus a little, but to increase the non-uniformity by a factor of 2, to 50%. Parabola/1 on the other hand has such severe aberrations that the spot shape was neither symmetric nor flat topped.

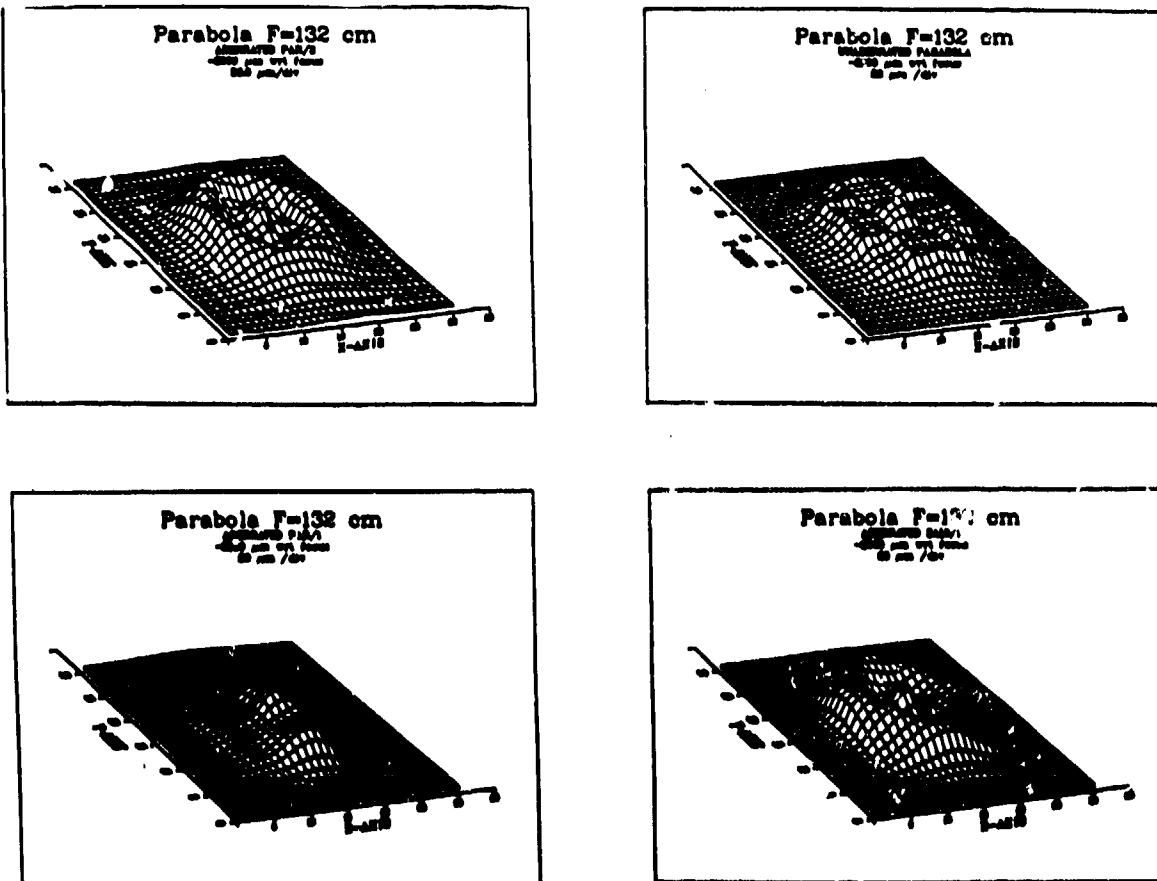


Fig. 2. Effect of aberrations at a fixed focal length. a) aberration due to parabola/2; b) aberration due to the older parabola/1; c) aberration due to a salt window; and d) reference case of no aberration.

In addition to the aberration of the focusing optics Figs. 2 and 3 show the effect of a salt window (before the parabola) on the intensity distribution. Its effects were similar to, but more severe than, the parabola/2,. Changing the axial position did not produce a uniform distribution over a 500 μm diameter spot size.

Effect of the focal length

While a 500 μm geometric spot size required an axial position $\sim 2000 \mu\text{m}$ inside the focus of a 132 cm parabola, a parabola with focal length 78 cm required an axial position $\sim 1100 \mu\text{m}$ inside the focus. Figures 4 and 5 demonstrate the effect of the focal length on the aberrated beam.

It is seen that for moderate aberrations the shorter focal length intensity distribution had more structure, as expected from diffraction theory. However, the uniformity for shorter focal length defined as

$$\text{Uniformity} = (\text{Peak-Valley})/(\text{Peak+Valley})$$

(8)

was reduced from 50% at 132 cm to 37% at 78 cm. Equally as important the average intensity for the 78 cm parabola was also higher by about 70%.

For a severely aberrated parabola, Fig. 6 shows the effect of the focal length. The 132 cm focal length is more uniform and more closely approximates the geometric spot size. However, both distributions are not useful for good shock wave experiments.

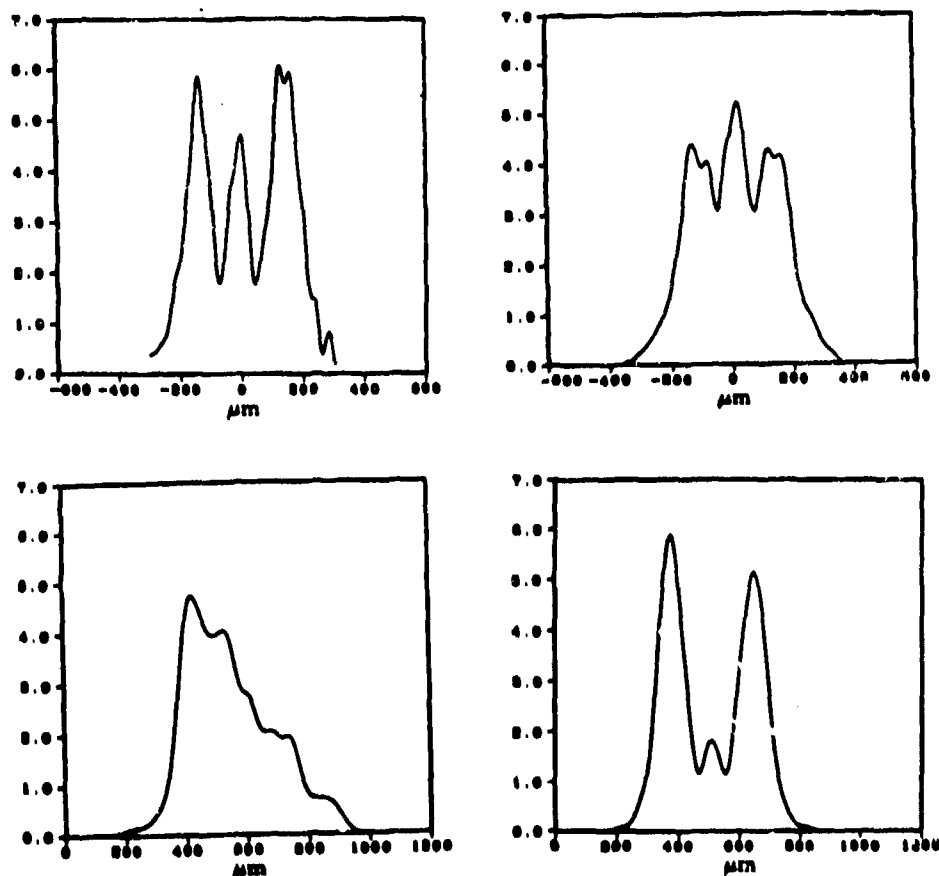


Fig. 3. Effect of aberrations at a fixed focal length. A slice of the intensity distribution parallel to the y axis at $x = 0$. a) aberration due to parabola/2, b) aberration due to the older parabola/1, c) aberration due to a salt window, and d) reference case of no aberration.

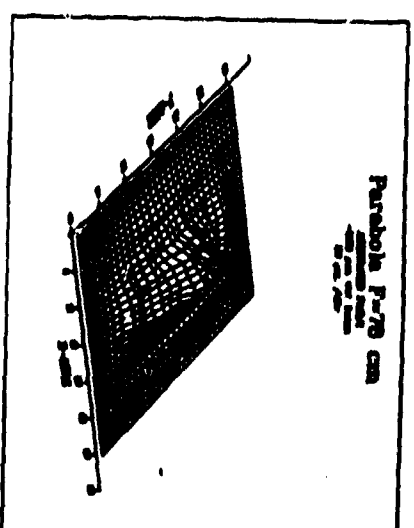
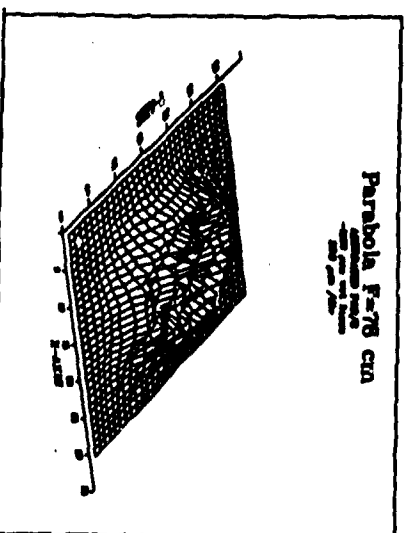
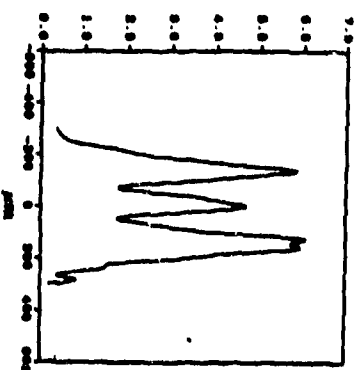
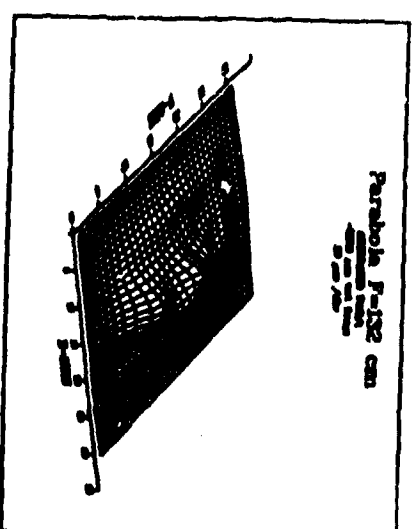
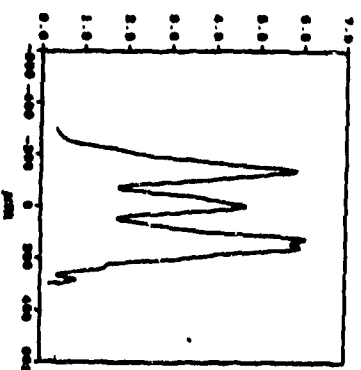
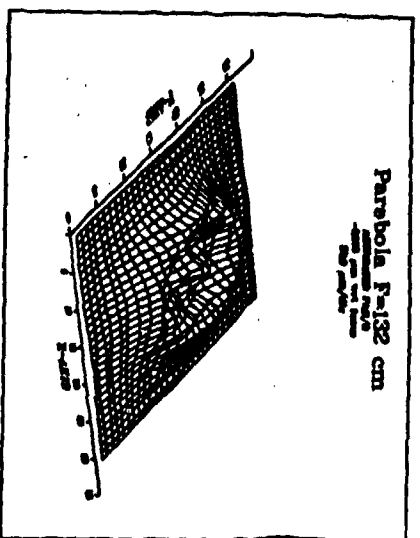


Fig. 4. Effect of focal length at constant moderate aberration.
a) focal length = 132 cm ($f/3.8$)
b) $f = 78$ cm ($f/2.2$)

Fig. 5. Effect of focal length at constant moderate aberration.
a) focal length = 132 cm ($f/3.8$)
b) focal length = 78 cm ($f/2.2$)

Fig. 6. Effect of focal length at constant severe aberrations.
a) $f = 32$ cm ($f/3.8$)
b) $f = 78$ cm ($f/2.2$)

Conclusion/Summary

The study shows that for moderate optical aberrations, the shorter focal length focusing optics tend to give more uniform, higher average illumination intensity, but more structured illumination, within a 500 μm laser spot size than using the longer focal length optics. On the other hand, for strong aberrations, there is a very slight advantage to using longer focal length optics. Longer focal length optics has another advantage, namely, less sensitivity to axial positioning errors.

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